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Optimal military transportation in a Korean wartime theater

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THESIS

OPTIMAL MILITARY TRANSPORTATION IN A KOREAN THEATER

by

Young-Sik Jeong

December 2006

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Second Reader:	Sergio Posadas

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OPTIMAL MILITARY TRANSPORTATION IN A KOREAN WARTIME THEATER

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Submitted in partial fulfillment of the requirements for the degree of

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Due to their high dependency on highway transportation, Republic of Korea's (ROK's) military and industry suffer from congestion, shortfall of means (convoys in the military case), high cost and increase in environmental damage. Our research develops an optimization model to guide ROK's military planning using multi-modal transportation. We apply our Military Logistics Transportation Model (MLTM) to a realistic scenario. MLTM provides guidance on the optimal frequency of transportation services and the optimal routes for the freight. By comparing the solution of MLTM with current practice for Wartime Transportation Planning (represented by a heuristic method), our MLTM can reduce the transportation cost up to 29%. This is enabled by the activation of multi-modal transportation and service sharing by multiple demands. We also analyze scenarios in which either sea-port of debarkation (SPOD) where the supply originates has been shut down by enemy attacks. We find that losing Busan SPOD is more damaging than losing Kwangyang SPOD.

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DISCLAIMER

All the military terminology and names are translated by the author and then it might not be proper to use them in official documents. The data in this thesis have been assumed and approximated for this study since the real data are kept classified. The views expressed in this thesis are those of the author and do not reflect the official policy or position of the ROK Ministry of Defense or U.S. Government.

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

ARRS	Army Re-supply Requirements Scenario
DMZ	De-Militarized Zone
DTC	Defense Transportation Command
GAMS	General Algebraic Modeling System
GSMA	Greater Seoul Metropolitan Area
KTX	Korean Train Express
LSC	Logistics Support Command
MLTM	Military Logistics Transportation Model
MSR	Main Supply Routes
ROK	Republic of Korea
SPOD	Sea Port of Debarkation
TEU	Twenty-foot Equivalent Unit
WTP	Wartime Transportation Plan

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The more I learn, the more I know how much I do not know. I have been very happy to gain new knowledge for these past two years at the Korean National Defense University and the Naval Postgraduate School. I would like to express my gratitude to the memory of Captain King, who gave me confidence and opened the possibility of changing my problem to a thesis subject, and am deeply sorry not to be able to thank him myself since he passed away last summer. I also would like to thank Lieutenant Colonel Sergio Posadas for reviewing this thesis in detail, and my thesis advisor, Professor Javier Salmeron for his dedicated effort, patience and inspiration. I am particularly grateful to the faculty of the Korean National Defense University for providing me with such a great opportunity. Last but not least, I would like to express my gratitude to my wife, two children and yet-to-be-born baby. Living and studying alone here in Monterey was not easy, but I overcame every difficulty with their support and understanding, and knowing that I would soon return to Korea to be reunited with them. Always, I will return all my honor and success to God. The Lord is my shepherd who provides everything I need.

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EXECUTIVE SUMMARY

The Republic of Korea's (ROK's) transportation infrastructure is unique. The Great Seoul Metropolitan Area (GSMA) includes 23 million people and is ROK's economic and culture center. Supporting traffic flow between several major cities and the GSMA is a core of ROK's transportation infrastructure.

In spite of recent improvements in ROK's transportation environment, the overall transportation condition in ROK has not improved due to a parallel increase in industry activities. Both military and industry transportation suffer from highway congestion, shortfall of transportation means (convoys in the military case), and high transportation cost, and continue to cause increased environmental damage. However, similar to civil industry freight transportation, a large portion of military demand in the current Wartime Transportation Plan (WTP) is still expected to be transported by highway, due to transportation speed and convenience. Our work suggests using multi-modal transportation, which can be more vigorously carried out after the recent development of seaports and railways in ROK.

In this thesis, we study a military, long-haul transportation problem, using a service network design, and multi-modal transportation which includes highways, railways, and waterways. The formulation of our Military Logistics Transportation Model (MLTM) relies on the concepts of service network and routes for the demand. A route for a given demand consists of a set of sections in specific services, along with the information of transportation modes, transfers and cost, between the source and the destination nodes. A route may be composed of a combination of different services and transportation modes. Routes are generated in advance in order to solve the problem efficiently.

We apply our formulation, MLTM to a transportation problem for ROK's military in a realistic scenario. The outcome of our MLTM is desirable for the military transportation planers to guide them on how to better establish the transportation services and allocate their resources.

By comparing the solution of MLTM with current WTP practice (which is reproduced by a heuristic method), our MLTM can reduce the transportation cost up to 29%. The main reasons for this result are: the activation of multi-modal transportation; service sharing by multiple demands, which is explicitly enabled in MLTM; and, the guarantee that the solution is optimal. The total share of convoy use decreases by 65% (from 69% in the heuristic to 4% in the optimal MLTM solution), but the percentages for train and ship increase by 28% (from 31% to 59%) and 37% (from 0% to 37%), respectively. Waterways are used at their maximum capability, as the most economical transportation means.

We have compared two single-SPOD scenarios, Busan and Kwangyang, under the assumption that either SPOD has been temporarily shut down by enemy attacks. Both scenarios can meet the demand, but we find that losing Busan SPOD is more expensive than losing Kwangyang SPOD. In case of using Busan SPOD only, the total transportation cost is 3.7% higher than using both SPODs, but 5.0% lower than using Kwangyang SPOD only. In the Busan SPOD scenario, more train services and less convoy services are needed than in the Kwangyang SPOD scenario. This, which bears most of the total cost difference, is explained because Busan SPOD has a well-developed railway infrastructure.

I. INTRODUCTION

A. BACKGROUND

The Republic of Korea's (ROK's) transportation infrastructure is unique. The country covers 98,480 km² in land mass [CIA, 2006]. ROK has nine provinces and seven metropolitan cities: Seoul, Incheon, Kwangju, Busan, Taegu, Taejon, and Ulsan. Three of these are major ports: Incheon, Busan and Ulsan. See Figure 1. The ROK's population is approximately 48.8 million. The country's capital, Seoul, is located on the border with North Korea and has a population of 10.5 million [USFK, 2006]. This city is home to 21.5% of the entire country's population. The Greater Seoul Metropolitan Area (GSMA) encompasses Seoul and its surrounding areas (including Incheon). The GSMA includes 23 million people, 47.1% of the country's population is centered in northwest corner of ROK.

Figure 1. **GSMA and major cities in ROK peninsula [after CIA, 2006]**

The GSMA is the ROK's economic and cultural center. The ROK transportation infrastructure focuses on supporting traffic flow between the other five metropolitan cities and the GSMA. ROK's mountainous terrain severely limits the layout of roadways and railways. The ROK is a peninsula with only 238 km of land boundaries (with North Korea) compared to 2,413 km of coastline. The country's geographical nature further constrains the transportation infrastructure.

Over the past ten years, ROK's transportation infrastructure has evolved notably, and changes are expected to be even more significant in the next five years. As an example, Busan (the second largest city in Korea) has been constructing a second port that will be fully operational in 2011 [BPA, 2005]. Another remarkable development is the high speed Korean Train Express (KTX), which started to operate in 2004. The whole KTX line is expected to be in service by 2010 [KRC, 2005]. See Figure 2. Highway construction and expansion has also increased over the last few years. For example, "expressway 15" opened in 2003, and is contributing to accessibility and development of the south-west region of ROK; "expressway 45" opened in 2005, alleviating traffic congestion on "expressway 1", which is a main route from Seoul to Busan [KHC, 2006].

Figure 2. **Korean Train Express and new Busan port [from KRC, 2006 and BPA, 2005]**

In spite of these efforts to improve ROK's transportation environment by highway, railway, and even sea, the overall transportation condition in ROK has not improved due to a parallel increase in industry activities. This is regarded as one of the most significant problems of ROK's industry development. According to the announcement by ROK's government, the cost caused by traffic congestion is 23 billion dollars in 2004 (2.3% of Gross Domestic Product) [MOCT, 2006]. A survey in this article shows that over 77% of freight transportation is done by highway (Figure 3). This causes other side effects such as large amounts of fuel consumption, increase in cost for industry activity, and increase of pollutant emissions.

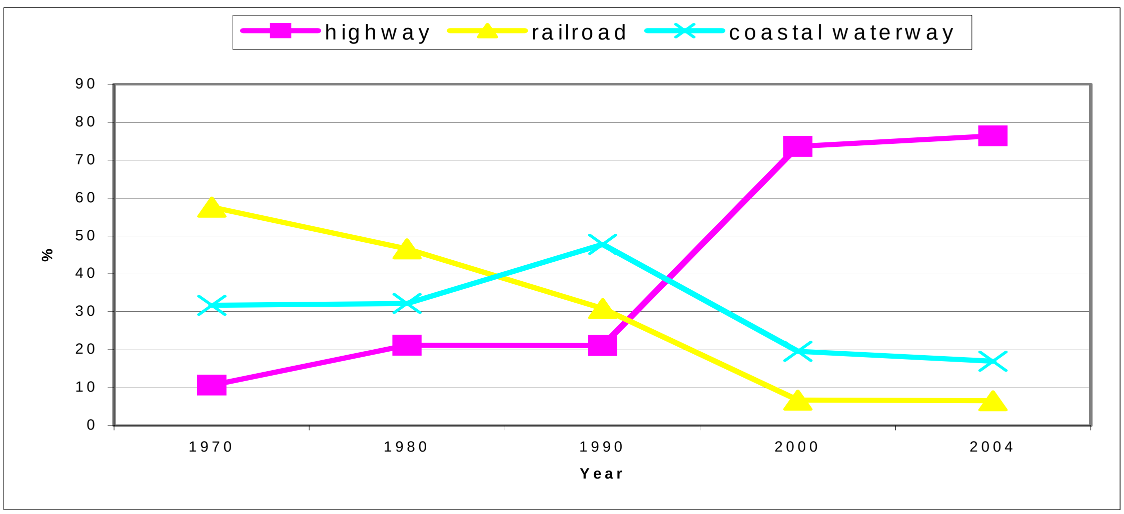

Figure 3. **Evolution of transportation share in ROK [after MOCT, 2006]**

The military faces similar difficulties to those of civil industry. Historically, most of wars demonstrate shortfalls in transportation assets and resources. Battle commanders want to ensure they can move their reserves and vital re-supply to the right place and at the right time. This suggests that fast convoys should be reserved for emergency military use, whereas trains and ships may support regular transportation demand. Similar to civil industry freight transportation, a large portion of commodities in the current Wartime Transportation Plan (WTP) is supposed to be transported by highway due to transportation speed and convenience. Economical aspects not considered in the WTP motivate this study.

Both military and industry transportation by highway suffer from congestion, shortfall of transportation means (convoys in the military case), high transportation cost and environmental damage [Lee, J. S., 2004]. However, since ROK is a peninsular country, it can take advantage of a multi-modal network consisting of highways, railways and waterways. Recent development of seaports and railways will allow multi-modal transportation more vigorously in ROK. However, there are several aspects to be considered in order to make multi-modal transportation address the problem of freight transportation growth. Critical weaknesses of a multi-modal transportation system include the large amount of fixed cost for operating each service, and the excessive time to transfer between modes. In this thesis we show the possibility of adopting multi-modal transportation in ROK military planning.

B. MILITARY TRANSPORTATION NETWORK IN ROK

The primary military operation against a hypothetical invasion of ROK by North Korea would be to protect the capital Seoul and to block North Korea at the military demarcation line along the De-Militarized Zone (DMZ). The DMZ is 4 km wide and 250 km long and it was formed in 1953 after the Korean War [Deane, 1999]. To succeed in that goal, it is necessary to guarantee seamless logistics support and rapid unit deployment from Sea Ports of Debarkation (SPODs) to the units' location. Busan, the second largest city and the first largest seaport in ROK, has played a key role as SPOD over the last 50 years. More recently, the Kwangyang port has been built in the southwest region of ROK to lighten the burden on Busan. The ROK's military transportation backbone connects Seoul (and the other cities near the DMZ) and several SPODs, including Busan and Kwangyang. See Figure 4.

Highways in ROK can be classified into expressways and freeways. All expressways are toll highways operated by Korean Highway Corporation and, as of 2004, they extend through 2,923 km [KHC, 2005]. Expressways (solid lines in Figure 4) have a key role in connecting the ROK peninsula. In this thesis, we consider all expressways and the some freeways (dotted lines in Figure 4) where there are no expressways. Some

of these highways are reserved for military transportation during wartime, and are called Main Supply Routes (MSRs). ROK Army Logistics Support Command (ROKA LSC) and Defense Transportation Command (DTC) manage several transportation groups, which will be mobilized in wartime. Convoys composed of trucks in these groups are the major transportation means using highway.

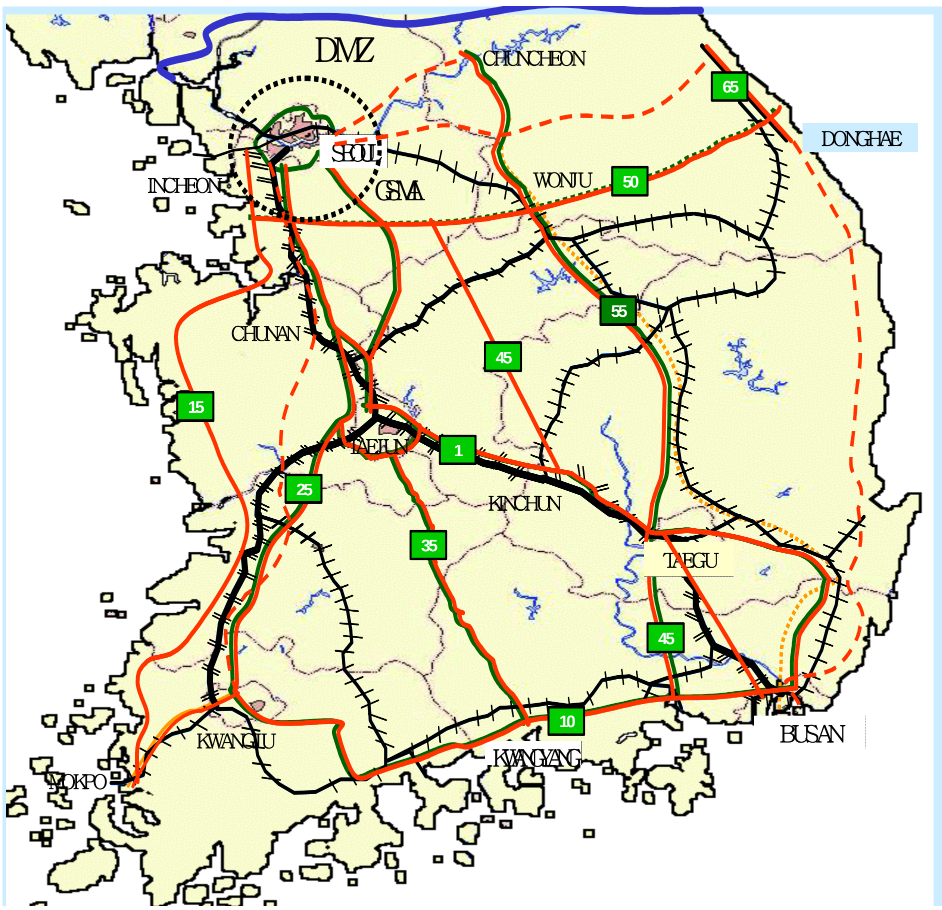

Figure 4. **Highways and railways in ROK**

Railways in ROK have served passenger and freight transportation for over 100 years and still share an important portion of ROK's transportation. In fact, railways are becoming an increasingly important transportation means for long distance passengers due to highway congestion caused by the steep increase in motoring population. The total railroad network is 6,240 km in length, with additional 409 km of the new KTX line which features top speeds of 350 km/h [KRC, 2005]. By the agreement with Korean Railroad Cooperation, military forces can use the whole railway network during wartime.

Given the current fleet of locomotives and railcars, a maximum of 350 trains can be composed. Railway transportation is more stable than highway because it is not affected by congestion uncertainty: Deliveries can be made as scheduled.

ROK's domestic coastal waterways are not yet sufficiently developed to compare to railways and highways. However, ROK has well-developed seaports and operates one of the largest merchant fleets that sail regularly to China, Japan, and the Middle East. At present, the coastal waterways are considered an important alternative to reduce traffic congestion and logistic cost in the industry. The Seaport Management Group in the DTC operates and develops seaports for military use in war and peace time and commercial ships are planned to be mobilized in wartime to support military transportation demand in coastal waterway.

C. FREIGHT TRANSPORTATION CLASSIFICATION

In this thesis, we are solving a long-haul freight problem, using a service network design, and multi-modal transportation. We introduce the common classification of freight transportation and recent studies to help understand these concepts.

Freight transportation involves producers, carriers and government. Producers want to move the raw materials or final products to the consumers at low price and as far as possible, within a required time. Carriers use trains, trucks, ships, and aircraft. Governments contribute to construct and regulate the infrastructure of transportation.

We can classify freight transportation problems from a planning and operation point of view, the human and material resources they use, and the planning horizon [Hall, 2002]:

- Long-haul vs. local transportation

The long-haul transportation problem is concerned with the movement of goods over relatively long distances, between terminals or cities, prioritizing economies of scale. Local vehicle routing and distribution problems handle more detailed

issues such as the shortest way for delivering in a small region, and the delivery schedule, focusing more on customer service.

- Multi-modal transportation, carrier network and services

Multi-modal transportation benefits from several modes to move commodities, but does not require interoperability between modes. Inter-modal transportation is the interaction of several transportation modes including the transfer of commodities among them. Carrier networks and services determine the service network design, frequency, scheduling, and terminal and line-haul operations.

- Consolidation vs. customized transportation

Consolidation transportation refers to an established regular carrier service to satisfy the largest number of customers within a specified region by the principle of economics. It is often associated with a schedule that indicates departure and arrival times at the stops along a route. On the other hand, customized transportation provides direct service to each customer, and it is known as "door-to-door" transportation.

- Strategic, tactical, and operational planning

Strategic planning applies to international, national and regional transportation levels of planning with investment over long-term horizons. The design of the physical network and the location of major logistics terminals are considered at this level. Tactical planning aims to determine efficient allocation or utilization of resources to achieve the best possible performance of the whole system. The design of the service network is a typical example of tactical level decisions, and it concerns issues such as determining services between locations and their schedules. Operational planning is performed by local management and dispatchers. It occurs in a very dynamic environment so that factors such as time, detailed vehicle movement and terminal operation are considered essential.

Recent research that applies optimization models to freight transportation, is relevant to this problem. For example:

Marin and Salmeron [1996] design a service network for rail freight transportation. The objective of the model is to decide the optimal assignment of trains to the service network, and simultaneously assign railcars to routes. They incorporate features such as railcar transfer and classification, different capacities, and a limited fleet of trains available for use. They propose exact and heuristic methods to solve this problem.

A Menlo Worldwide project team [Prior et al., 2004] develops an optimization model to solve scheduling and routing of an integrated aircraft and truck network in the U.S. This research is a good example of inter-modal, freight transportation problem. The model is difficult to solve as a whole, and needs to be decomposed into two phases, where all serviceable routes are pre-generated.

Pedersen [2005] studies planning issues within inter-modal transportation in his dissertation, Optimization Models and Solution Methods for Inter-modal Transportation. His work proposes models and algorithms for optimizing schedules in the consolidated inter-modal transportation networks, focusing on tactical level planning. The third part of his work, entitled *Optimization of Inter-modal Freight Train Service Schedules on Train Canals*, presents a mathematical model for inter-modal train scheduling with incorporation of terminal operation, inventory, and delivery times in the rail sector in Europe. The paper shows that combining different exact and heuristic approaches could contribute to find a near optimal solution effectively.

D. THESIS OBJECTIVES

This work focuses on the tactical transportation problem of military cargo containers. We seek the effective allocation of existing resources to meet the military freight transportation needs during war time.

Specifically, this thesis presents optimal transportation logistics for ROK military by ROK Army's re-supply requirements scenario (ARRS). Our research considers multiple sources and destinations, and a multi-modal transportation network with transfers, where the service network includes highways, waterways and railways. The

freight in ARRS is not an emergency commodity but regular re-supply. We develop an optimization model to guide ROKA LSC's allocation of existing resources in order to minimize total transportation cost plus penalties for failing to meet the demand. We demonstrate the model over existing, manual planning, in several instances of ARRS.

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II. MODEL FORMULATION

A. TERMINOLOGY

The formulation of our MLTM is based on the model by Marin and Salmeron [1996] for rail freight transportation. The MLTM considers a multi-modal network. We generate the anticipated, plausible routes in advance to solve the problem efficiently. To help understand our formulation, we first describe the concepts of physical network, service network, demand and routes:

- Physical network: The physical network is represented by nodes and arcs linking them. Nodes represent sea ports, truck terminals, and rail stations; arcs represent highways, railways, and waterways. (The physical network used in our test cases is depicted in section III, Figure 8.)

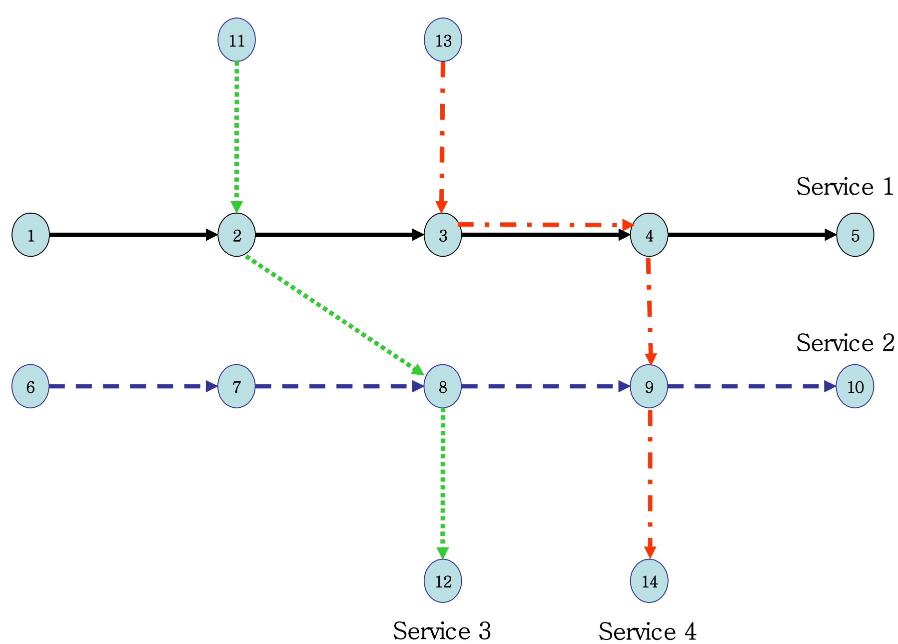

Figure 5. **Service network [after Marin and Salmeron, 1996]**

- Service network: A service is characterized by an origin node, a set of transshipment nodes, and a destination node. Figure 5 shows four services: 1-2-3-4-5, 6-7-8-9-10, 11-2-8-12, and 13-3-4-9-14. These services provide

transportation with a frequency to be determined by our model. A section (e.g., 3-4) in a service is a physical segment between two nodes, which represents, for example, a track of the railroad network, and may be shared by more than one service.

- Demand: A demand is characterized by its potential origins and a destination node in the physical network, as well as the amount of cargo required. Two demands may have the same origin and destination nodes if, for example, they have different transportation costs. Any demand can be moved from its sources to the destination using one or several routes available for the demand. (See below.)

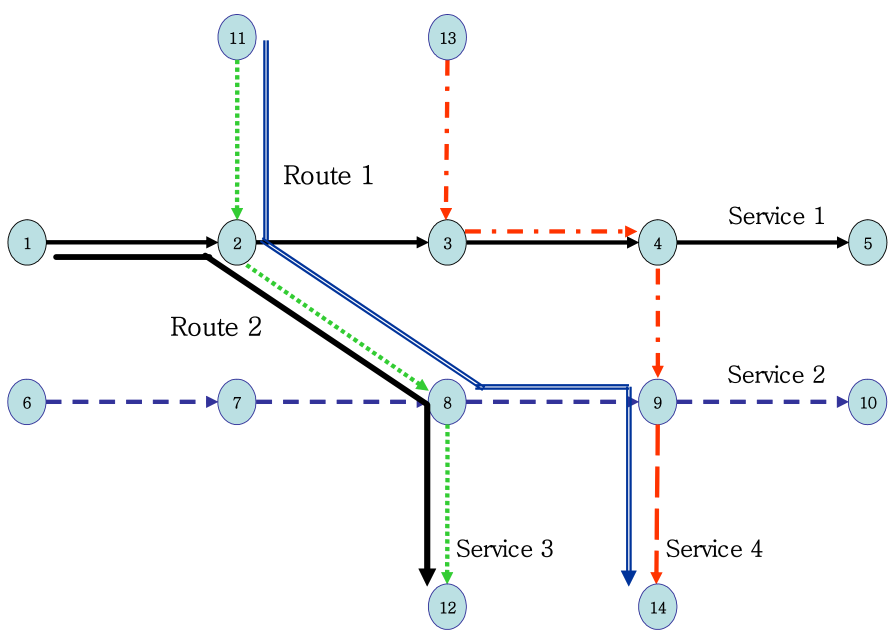

Figure 6. **Routes in the physical network [after Marin and Salmeron, 1996]**

- Routes: A route is a set of sections in specific services connecting one demand source and its destination. It may be composed of a combination of different services and transportation modes. In our MLTM, the routes using just convoys comprise just one transportation service, but the routes using trains and ships need trucks to finish the delivery. Figure 6 shows examples of routes in the service network. Route 1 (11-2-8-9-14) has four sections and

uses three different services, whereas Route 2 (1-2-8-12) has three sections and two services. An alternative route between node 11 and node 14 would be, for example, 11-2-3-4-9-14, using five sections and three services. This route must specify whether the transfer between services 1 and 4 occurs at node 3 or at node 4.

In our MLTM, the concept of route is instrumental. Each route has information on transportation modes, services, transfers, and cost, between every source and the destination nodes for each demand. Generating plausible routes is required as preparatory work in this model.

B. MATHEMATICAL FORMULATION

This section presents the formulation of MLTM as an optimization model.

1. Sets and Indices

M, transportation modes,

$$m \in M = \{CONVOY, TRAIN, SHIP, TRUCK\}$$

S, services, $s \in S$

C, sections, $c \in C$

R, routes, $r \in R$

W, demand, $w \in W$

P, sea ports of transshipment, $p \in P$

$R_w \subset R$, subset of routes for demand w

$R_c^1 \subset R$, subset of routes using section c

$R_s^2 \subset R$, subset of routes using service s

$C_s \subset C$, subset of sections in service s

$S_m \subset S$, subset of services using mode m

$S_p \subset S$, subset of ship services using sea port of transshipment p

2. Parameters (Units)

horizon, planning horizon (days)

$fleet_m$, available fleet of mode m (number of convoys, trucks, trains, or ships)

$freqCost_s$, frequency cost for service s (\$/trip)

cap_s, capacity of service s (TEUs/trip)

$time_s$, round trip travel time of service s (days/trip)

$portLim_p$, capability of transshipment port p for ship entering to unload cargo (trips/day)

Remark: In actuality, the capacity is given is ships/day based on unloading time at the port; however, we use trips/day to be consistent with our unit of frequency.

$limit_c$, capacity of section c (trips/day)

dem_w, amount of demand w (TEUs/day)

$penalty_w$, penalty for unmet demand w (\$/TEU)

$routeCost_r$, transportation cost using route r (\$/TEU)

$avail_r$, available supply on the route r (i.e., supply at the origin of the route for the demand associated to route r) (TEUs)

3. Decision Variables (units)

X_r, freight delivered by route *r* (TEUs)

Y_s, frequency of trips on service *s* (trips)

U_w, unmet amount of demand *w* (TEUs)

4. Mathematical Formulation

Minimize

$$\sum_{r \in R} routeCost_r X_r + \sum_{s \in S} freqCost_s Y_s + \sum_{w \in W} Penalty_w U_w \tag{1}$$

Subject to:

$$\sum_{r \in R_w} X_r + U_w = horizon \cdot dem_w, \qquad \forall\ w \in W \tag{2}$$

$$\sum_{r \in R_c^1 \cap R_s^2} X_r \le cap_s Y_s, \qquad \forall c \in C_s, \forall s \in S \tag{3}$$

$$\sum_{s \in S_m} time_s \cdot Y_s \le horizon \cdot fleet_m, \qquad \forall m \in M \tag{4}$$

$$\sum_{s | c \in C_s} Y_s \le horizon \cdot limit_c, \qquad \forall c \in C \tag{5}$$

$$\sum_{s \in S_p} Y_s \le horizon \cdot portLim_p, \qquad \forall p \in P \tag{6}$$

$$0 \le X_r \le avail_r, \qquad \forall r \in R \tag{7}$$

$$Y_s \in \{0, 1, 2, \cdots\}, \qquad \forall\ s \in S \tag{8}$$

$$U_w \ge 0, \qquad \forall w \in W \tag{9}$$

5. Description of the Formulation

a. Objective Function (1)

We minimize the sum of three costs: First, the frequency cost related with trips made, regardless cargo. For example, it includes the cost of composing a train, paying a driver, etc. Second, routing costs by unit associated with handling cargo, fuel consumption, etc. Third, we define a penalty that reflects a subjective value of military operational cost for unmet demand.

b. Demand Constraints (2)

In our model, cargo from an origin to a destination node can be delivered using several routes. The total freight on these routes should equate the demand requirement, after accounting for unmet demand.

c. Service Capacity Constraints (3)

Freight on the routes sharing a service cannot exceed the capacity of the service. Since the route consists of several sections, freight on the route is limited by the capacities of the services used by the route.

d. Fleet Capacity (4)

The total frequency assignment across all services of a given transportation mode cannot exceed the available fleet of that mode.

e. Section Capacity Constraints (5)

The frequency on a service should be limited by the total use of the service sections, i.e., not just by that service, but also by other services using the same section(s). e.g., a maximum number of trains per day can traverse a rail track, although they may serve different services.

f. Port Capacity Constraints (6)

Each sea port of transshipment has a limited capacity to handle ships. Remark: The constraint could also be formulated in terms of cargo.

g. Variable Domain (7)-(9)

Freight and unmet demand variables are allowed to take continuous values because they represent TEUs of cargo. Freight on a route is limited by the supply at the origin of the route. Frequency on the services is forced to be an integer number of trips.

III. SCENARIO DESCRIPTION

This chapter describes a hypothetical scenario based on ARRS.

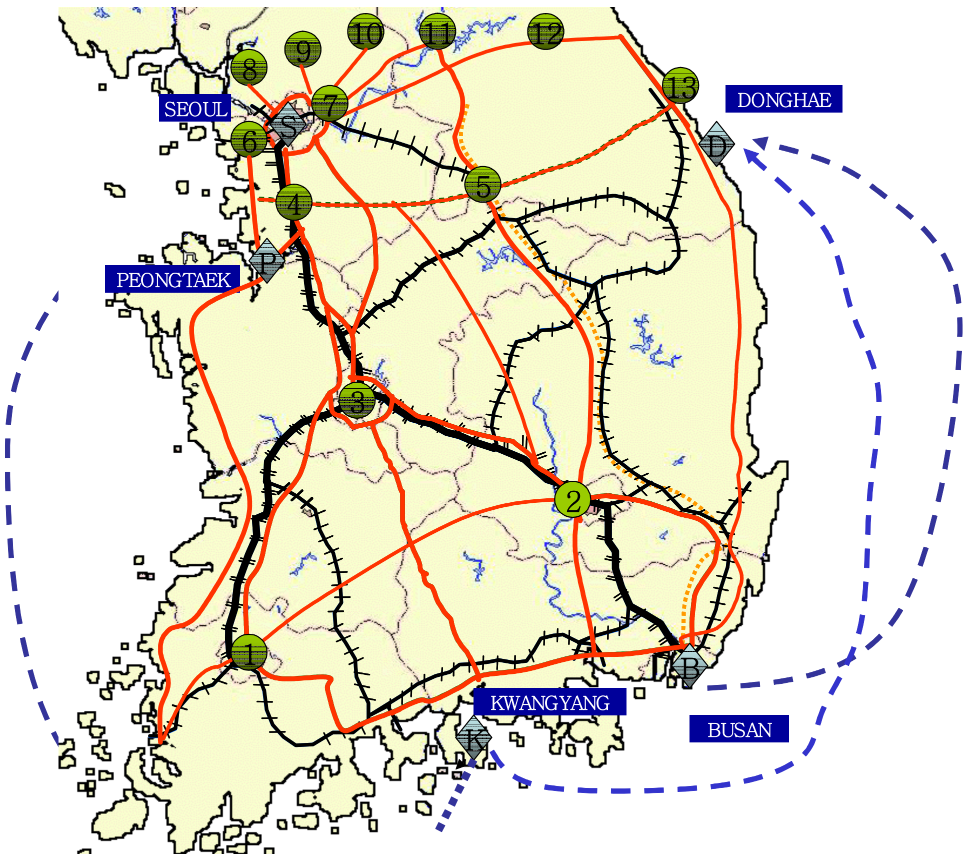

Figure 7. **Military transportation network in ARRS**

A. MILITARY TRANPORTATION NETWORK IN ARRS

ARRS considers only two source nodes: Busan and Kwangyang SPODs. These are vulnerable to enemy missiles, so we consider three possible scenarios: two scenarios have either SPOD destroyed, and one scenario has both SPODs available. We have thirteen destinations scattered across ROK, albeit mostly concentrated in the north, near the DMZ (see Figure 7). The destination nodes represent locations which are substituted by the cities near the DMZ and transportation hubs in ROK.

Figure 8 shows source, destination and junction nodes, as well as transportation modes in our ARRS. We assume the ROK military forces can use this transportation network with the highest priority in war time: This means that military transportation demand is allowed to be delivered without any waiting or delay by the civil transportation requirement depending on the commodity. This may be an optimistic assumption: even during wartime, military transportation may undergo congestion [Lee, J. S., 2004].

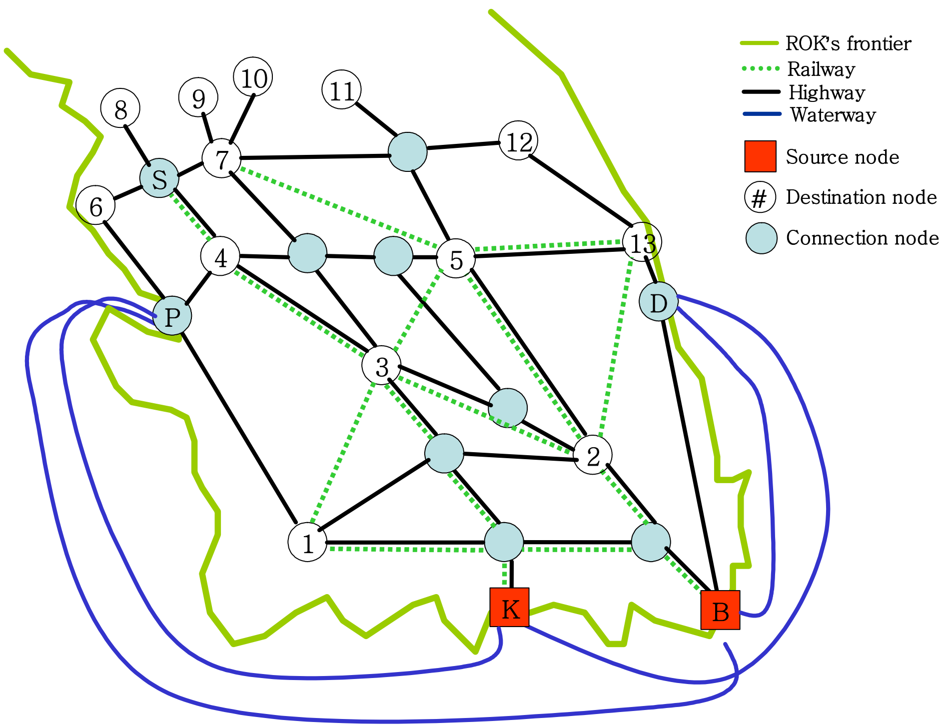

Figure 8. **Physical transportation network**

Highways are used by convoys (which consist of ten trucks each) and railways are used by seven different train services. Waterways are used by four different coastal transportation services in our model. Individual trucks are also used for local transportation from transshipment nodes (train stations or sea ports) to destination nodes, using highways. The transfer between modes is allowed just once, from either trains or ships to trucks. We have not explored the use of routes that allow more than one transfer, but this would be easy to accomplish by simply pre-generating these routes and adding them to our set *R*.

Table 1 shows all of the services in our model and Table 2 presents several examples of routes with specification of sections and cost.

Mode	Departure node	Services
Convoy	Bu-san	B-1, B-2, B-3, B-4, B-5, B-6, B-7, B-8, B-9, B-10, B-11, B-12, B-13
	Kwang-yang	K-1, K-2, K-3, K-4, K-5, K-6, K-7, K-8, K-9, K-10, K-11, K-12, K-13
Train	Bu-san	B-2-3-4-S, B-2-5-7, B-1-3-4-S, B-13
	Kwang-yang	K-3-4-S, K-3-5-7, K-1-3-4-S
Ship	Bu-san	B-P, B-D
	Kwang-yang	K-P, K-D
Truck	Transshipment nodes (1,2,3,4,5,7,P,D,S)	From each transshipment node to select destination nodes (e.g., S-11, P-4)

Table 1. **Service networks in ARRS**

Route code	Departure / Destination	Section	Service	Cost ($/TEU)
R1	Busan(B) / Kwangju(1)	Hw_B_1	B-1	427.2
R23	Bu-san(B) / Youngin(4)	Rw1_B_2 Rw1_2_3 Rw1_3_4	B-2-3-4-S (same) (same)	320
R60	Bu-san(B) / Chuncheon(11)	Rw3_1_3 Rw3_3_4 Rw3_4_S Hw_S_11	B-1-3-4-S (same) (same) S-11	540
R139	Kwangyang(K) / Youngin(4)	Ww_K_P Hw_P_4	K-P P-4	287.3

Table 2. **Sample routes and costs in ARRS**

B. TRANSPORTATION COST, CAPACITY AND DEMAND IN ARRS

Our model is mostly driven by transportation cost because we do not enforce time-window deliveries (as long as they occur within the planning horizon). This assumption is reasonable given that demand in our MLTM is regular military re-supply, not subject to emergency delivery (as would be unit movement or urgent need of ammunition).

We estimate transportation costs (service frequency and routing, respectively) as follows: The service frequency cost is a fixed cost to compose a train, ship, convoy or truck. It includes crew payments, depreciation expense of vehicles and other supplementary costs, so it is charged on a per-trip basis, regardless the amount of load. On the other hand, the routing cost is related to labor hours, fuel consumption, freight handling and distance, and is charged by weight. Generally, the military transportation cost is greater than the civil industry transportation. The difference is due to more expensive vehicles and crew labor cost, as well as poor gas mileage. Table 3 shows the military transportation cost assumed in our ARRS. We base our cost partition on the total cost for the equivalent civil transportation means by Kwun and Ha [2004], and the assumption that military transportation costs are 30% higher.

Mode		**Convoy**	**Train**	**Ship**	**Truck**
Frequency cost	$/service	500	4000	5000	50
Routing cost	$/(TEU·km)	1.6	0.8	0.4	1.6

Table 3. **Military transportation cost [after Woo, 2004]**

We consider four transportation modes whose available fleet and capacity are presented in Table 4. A convoy comprises ten trucks, each one capable of loading one TEU of cargo. A train has 25 railcars with two TEUs of capacity per railcar. The capacity of a ship is 225 TEUs, and 16 ships can be scheduled for domestic coastal transportation in ROK. The route time for a given period of convoys and trucks is calculated as indicated in Table 4. Considering the route time, we can use 33 trains and four ships per day. The MLTM considers section capacity to prevent congestion of some

of the cheapest services. Also, the Peongtaek and Donhae sea ports of transshipment can handle one ship per day each due to operational capability.

Fleet	On-hand (units)	Route time (day)	Capacity per unit (TEUs)
Convoy	432	Distance/Speed + transfer and rest time	10
Truck	540		1
Train	66	2	50
Ship	16	4	225

Table 4. **Available fleet and capacity [after Lee, J.S., 2004 and Lee, K. C., 2004]**

Node	Name	demand size (TEU/day)
1	Kwangju	47
2	Taegu	167
3	Tajeon	132
4	Yongin	128
5	Wonju	91
6	Inchun	51
7	Yjeongbu	145
8	Munsan	98
9	Pochun	92
10	Chulwon	81
11	Chuncheon	47
12	Injae	47
13	Gangneung	75

Table 5. **Transportation demand**

In our scenarios, we consider a generic commodity by TEU size container. A TEU includes military re-supply items such as food, clothes, fortification, ammunition, equipment, and repair parts (similar to class I, II, IV-VII, and IX supply by the United

States military system). The amount of demand is estimated as a function of the population size of the city. The amount of inventory stocked in each source node (SPODs Busan and Kwangyang) is enough to meet the whole demand, provided that they have not been shut down by an attack. Otherwise, the SPOD capacity is assumed to be zero. Thus, our MLTM decides the optimal amounts shipped from each SPOD. Table 5 shows the demand amounts represented by the re-supply requirement of ROK's Army per day.

IV. SOLVING THE MILITARY LOGISTICS TRANSPORTATION MODEL

In this chapter we present results to our scenarios obtained with MLTM. In addition, we outline a heuristic which resembles current methodology of WTP used by military transportation planners in ROK. We assess the heuristic under the scenario where both SPODs operate normally. The outcome generated by this heuristic reflects several shortcomings of the current WTP, such as concentration on the highway and neglect of economical considerations. We also compare the optimal solutions using one SPOD, i.e., under the assumption that either SPOD (Busan or Kwangyang) is shut-down by an enemy attack.

A. OVERVIEW OF THE HEURISTIC AND EXACT METHOD

The heuristic method follows commonly used assumptions by ROK's military transportation planners to address WTP. Some of the key ideas are based on the following guidance:

- We prefer to use convoys, if possible, rather than trains and ships (to avoid transfer of freight).
- We prefer to use one type of transportation mode for each demand (for planning convenience).
- We prefer to plan the demands on the west of ROK to be supplied from Kwangyang SPOD (due to shorter distance than Busan SPOD).
- Each trip made by any transportation means should be for at least 60% of its capacity (due to economical reasons).
- We prefer not to use ship services (for speed and planning convenience).

On the other hand, we implement MLTM as an optimization program in GAMS [Brooke et al., 1998]. Our mixed-integer program has 365 equations, 246 variables and 83 discrete variables, and is solved by XA [Sunset Software Technology, 2002].

B. COMPARING HEURISTIC AND EXACT SOLUTIONS

In this section, we compare the solutions to ARRS with both SPODs by using the heuristic and exact methods. The optimal solution to MLTM has an overall cost (routing plus service cost) of $463,049. The heuristic solution is almost 30% more expensive, which will be justified later in this section. Both solutions meet all the demand.

Node	Destination	Demand (TEU)	Heuristic Method		Exact Method	
			Route	Services used (convoy, train, ship, truck)	Route (TEU)	Services used (convoy, train, ship, truck)
1	Kwangju	47	R79	5, 0, 0, 0	R79 (47)	5, 0, 0, 0
2	Taegu	167	R2	17, 0, 0, 0	R2 (9)	1, 0, 0, 0
					R14 (154)	0, 4, 0, 154
					R33 (4)	0, 1, 0, 4
3	Tajeon	132	R81	14, 0, 0, 0	R92 (82)	0, 2, 0, 82
					R106 (50)	0, 1, 0, 50
4	Yongin	128	R96	0, 3, 0, 128	R96 (68)	0, 2, 0, 68
					R139 (60)	0, 0, 1, 60
5	Wonju	91	R5	10, 0, 0, 0	R75 (91)	0, 0, 1, 91
6	Inchun	51	R98	0, 1, 0, 51	R25 (51)	0, 2, 0, 51
7	Yjeongbu	145	R7	15, 0, 0, 0	R26 (145)	0, 3, 0, 145
8	Munsan	98	R102	0, 2, 0, 98	R143 (98)	0, 0, 1, 98
9	Pochun	92	R30	0, 2, 0, 92	R46 (92)	0, 2, 0, 92
10	Chulwon	81	R10	9, 0, 0, 0	R47 (14)	0, 1, 0, 14
					R145 (67)	0, 0, 1, 67
11	Chuncheon	47	R11	5, 0, 0, 0	R76 (12)	0, 0, 1, 12
					R41 (35)	0, 1, 0, 35
12	Injae	47	R12	5, 0, 0, 0	R77 (47)	0, 0, 1, 47
13	Gangneung	75	R13	8, 0, 0, 0	R78 (75)	0, 0, 1, 75

Table 6. **Summary of heuristic and exact solutions**

Table 6 presents the comparison summary. The solution by the heuristic method uses 13 routes (one per demand), whereas 19 routes are operated in the solution by the

exact method. For example, for the demand at Chulwon (node 10), the whole 81 TEUs are transported by route 10 (convoy from Busan SPOD) in the heuristic method; however in the exact method, 14 TEUs are transported by route 47 (train from Busan SPOD and then truck from Seoul) and the other 67 TEUs are transported by route 145 (ship from Kwangyang SPOD and then truck from Peongtaek). The exact method exploits the ability to split the demand into several routes, some using transfers between modes.

Figure 9 compares the transportation mode share provided by the heuristic and exact methods. In the heuristic solution, convoys transport 69% of total shipment, substantially more than trains (31%) or ships (0%). However, when we solve MLTM optimally, the use of convoys is reduced to 4% only, the use of trains increases to 59%, and the use of ships increases to 37%. The shift is due to the activation of multimodal transportation, which reduces total transportation cost.

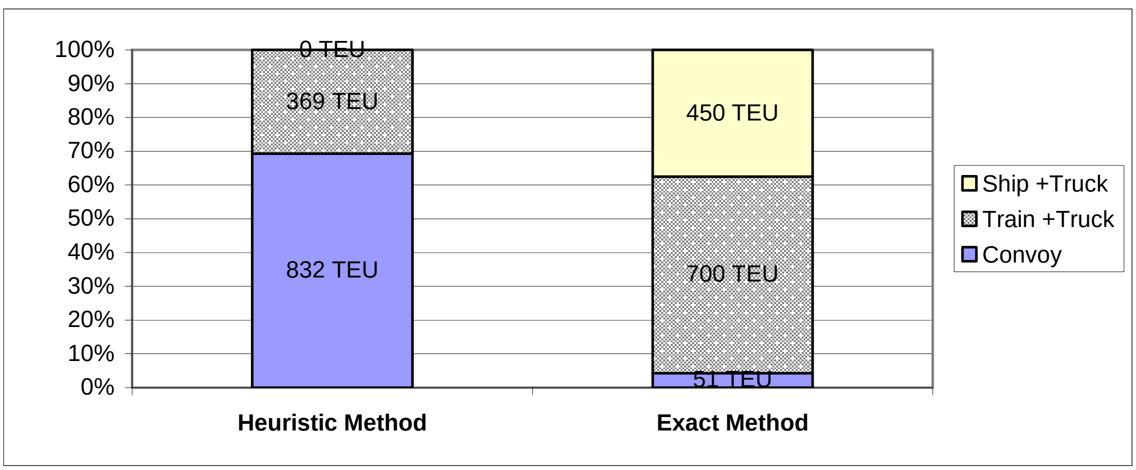

Figure 9. **Transportation mode share**

Table 7 shows service frequency. Convoy frequency in the solution by the exact method is reduced to six trips (from 88 by the heuristic method), all of which are allocated to demands within short distance of the origin, such as from Busan SPOD (node B) to Taegu (node 2), and from Kwangyang SPOD (node K) to Kwangju (node 1). Train and ship frequency in the solution by the exact method increases to 14 and two, respectively. Among the 14 train trips in the exact solution, ten trips are from Busan SPOD and the other four trips are from Kwangyang SPOD.

Mode	Heuristic Method		Mode	Exact Method	
	Service	Frequency		Service	Frequency
	B-2	17		B-2	1
	K-1	5	Convoys	K-1	5
	K-3	14		Total	6
	B-5	10		B-2-3-4-S	7
	B-7	15		B-2-5-7	3
Convoys	B-10	9	Trains	K-3-4-S	3
	B-11	5		K-3-5-7	1
	B-12	5		Total	14
	B-13	8		B-D	1
	Total	88	Ships	K-P	1
	B-2-3-4-S	2		Total	2
	K-3-4-S	6		2-2	163
Trains	Total	8		3-3	132
				4-4	68
				4-6	51
				4-7	145
Ships	Total	0		5-11	35
				7-9	92
	4-4	128		7-10	14
	4-6	51	Trucks	P-4	60
	S-8	98		P-8	98
	S-9	92		P-10	67
Trucks	Total	369		D-5	91
				D-11	12
				D-12	47
				D-13	75
				Total	954

Table 7. **Service frequency of requirements**

The busiest railway service in the exact solution is B-2-3-4-S (supporting 50% of total train frequency), which is the main railway service in ROK connecting Busan SPOD to Seoul. Two ship trips in our optimal solution is the maximum use of waterway service given the capacity of sea ports of transshipment (one ship per port per day). Remark: If the capacity at the sea ports of transshipment were increased to two ships per port, the total transportation cost would decrease to $441,474, using two trips per day to Peongtaek (node P) but still one trip to Donghae (node D).

As an example of train and ship service capacity being shared by several routes, we note the values associated with "Service used" in Table 6 and "frequency" of service in Table 7: We observe the sum of trains and ships from Table 6 is 19 and seven, respectively. On the other hand, "frequency" of service in Table 7 shows that just 14 trains and two ships are used.

Heuristic method		**Exact method**	
Transshipment node	**Trucks Required**	**Transshipment node**	**Trucks Required**
4	45	2	41
S	60	3	33
		4	17
		5	12
		7	29
		P	81
		D	84
Total	105	Total	297

Table 8. **Truck requirements**

Table 8 presents the number of trucks required at each transshipment node to complete the transportation to final destination nodes. In the heuristic method, 105 trucks are required at two railway stations. In our optimal solution, this requirement is increased to 297 trucks due to the increased use of railway and waterway services. Among these trucks, 132 need to be allocated to five railway transshipment stations (nodes 2, 3, 4, 5,

and 7), and 165 to two waterway transshipment ports (nodes P and D). From Table 8, and comparing with current WTP, it is clear that ROK's military can re-locate the truck resources and mobilize additional trucks in order to minimize costs.

C. SINGLE SPOD SCENARIOS

In this section we compare two optimal solutions, each with a single SPOD scenario. Our ARRS assumes the enemy has attacked one of the SPODs.

Table 9 presents the solution summary. In case of using only the Busan SPOD, all demand is met using one trip by convoy, 15 trips by train, two trips by ship and 1,001 trips by truck; the total transportation cost is estimated as $480,216, i.e., 3.7% higher than using both SPODs. Using only the Kwangyang SPOD, all demand is met with 22 trips by convoy, 11 trips by train, two trips by ship and 987 trips by truck; the total cost is $504,052. There is no significant difference in the total number of routes used in the Busan SPOD scenario (17 routes) and Kwangyang SPOD scenario (16 routes). However, in the Busan SPOD scenario, there are more train services and less convoy services used than in the Kwangyang SPOD scenario, which causes the difference in total cost. Figure 10 shows the difference in total transportation cost in each scenario.

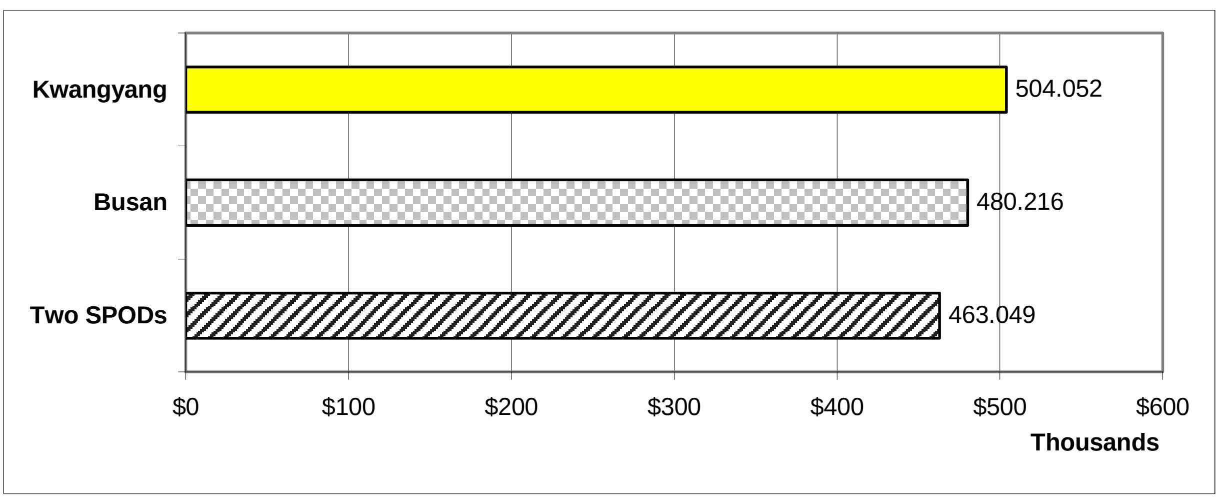

Figure 10. **Comparing transportation cost between single-port and two-port systems.**

Node	Destination	Demand (TEU)	Busan SPOD		Kwangyang SPOD	
			Route (TEU)	Services used (convoy, train, ship, truck)	Route (TEU)	Services used (convoy, train, ship, truck)
1	Kwangju	47	R49 (47)	0, 1, 0, 47	R79 (47)	5, 0, 0, 0
2	Taegu	167	R2 (4)	1, 0, 0, 0	R80 (167)	17, 0, 0, 0
			R14 (121)	0, 3, 0, 121		
			R33 (42)	0, 1, 0, 42		
3	Tajeon	132	R19 (132)	0, 3, 0, 132	R92 (30)	0, 1, 0, 30
					R106 (102)	0, 3, 0, 102
4	Yongin	128	R23 (1)	0, 1, 0, 1	R96 (128)	0, 3, 0, 128
			R68 (127)	0, 0, 1, 127		
5	Wonju	91	R75 (91)	0, 0, 1, 91	R110 (1)	0, 1, 0, 1
					R146 (90)	0, 0, 1, 90
6	Inchun	51	R25 (51)	0, 1, 0, 51	R98 (51)	0, 2, 0, 51
7	Yjeongbu	145	R26 (145)	0, 3, 0, 145	R99 (145)	0, 3, 0, 145
8	Munsan	98	R72 (98)	0, 0, 1, 98	R143 (98)	0, 0, 1, 98
9	Pochun	92	R46 (92)	0, 2, 0, 92	R103 (46)	0, 1, 0, 46
					R144 (46)	0, 0, 1, 46
10	Chulwon	81	R47 (81)	0, 2, 0, 81	R145 (81)	0, 0, 1, 81
11	Chuncheon	47	R41 (35)	0, 1, 0, 35	R113 (47)	0, 1, 0, 47
			R76 (12)	0, 0, 1, 12		
12	Injae	47	R77 (47)	0, 0, 1, 47	R148 (47)	0, 0, 1, 47
13	Gangneung	75	R78 (75)	0, 0, 1, 75	R149 (75)	0, 0, 1, 75

Table 9. **Summary of solution using a single SPOD**

Figure 11 shows the share by transportation mode for each single SPOD scenario. In the Busan SPOD scenario, the solution suggests transporting most commodities by train and ship, and it is almost negligible by convoy. This is realistic because Busan SPOD has a well-developed railway system. However, if Kwangyang is the only SPOD available, the recommendation is the same for ships, but 18% is now carried by convoy instead of train.

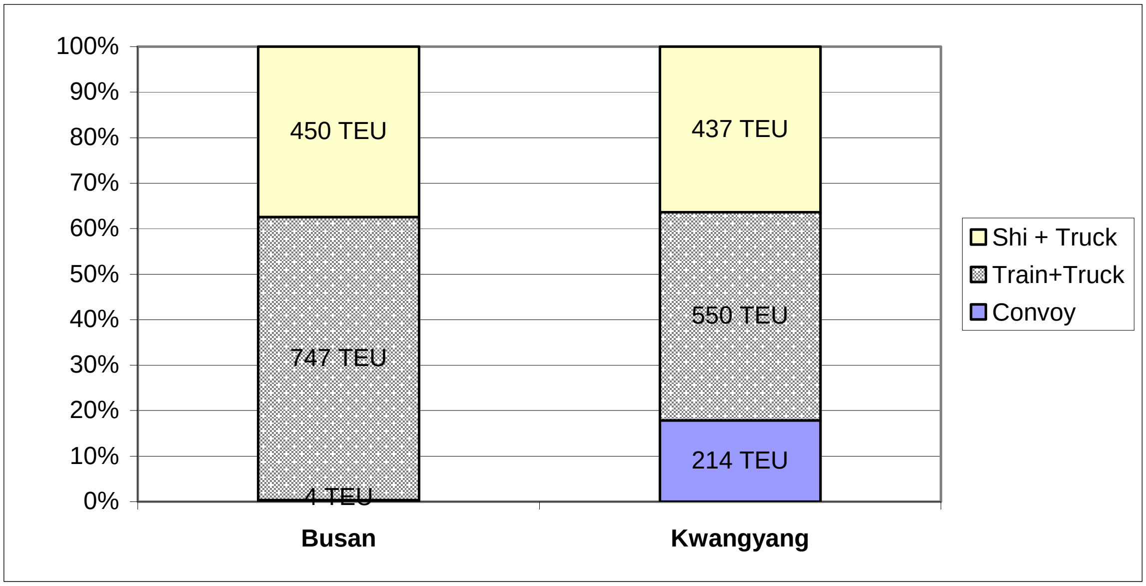

Figure 11. **Transportation mode share in the Busan-only and Kwangyang-only scenarios**

Table 10 shows the frequency of each service. In the Busan scenario, there is only one convoy trip, which serves the demand located at the shortest distance, to Taegu (node 2). However, in the Kwangyang scenario, 22 convoy types are used for two demands: to Kwangju (node 1) and to Taegu. The reason for an 18% convoy frequency increase in the Kwangyang scenario is that 17 convoy trips are allocated to the demand of Taegu, which is accessible only by highway.

Busan SPOD			Kwangyang SPOD		
Mode	**Service**	**Frequency**	**Mode**	**Service**	**Frequency**
Convoys	B-2	1	Convoys	K-1	5
	Total	1		K-2	17
Trains	B-2-3-4-S	9		Total	22
	B-2-5-7	5	Trains	K-3-4-S	8
	B-1-3-4-S	1		K-3-5-7	3
	Total	15		Total	11
Ships	B-P	1	Ships	K-P	1
	B-D	1		K-D	1
	Total	2		Total	2
Trucks	1-1	47	Trucks	3-3	132
	2-2	163		4-4	128
	3-3	132		4-6	51
	4-4	1		4-7	145
	5-11	35		5-5	1
	7-9	92		5-11	47
	7-10	81		S-9	46
	P-4	127		P-8	98
	P-8	98		P-9	46
	D-5	91		P-10	81
	D-11	12		D-5	90
	D-12	47		D-12	47
	D-13	75		D-13	75
	Total	1001		Total	987

Table 10. **Service frequency requirement using a single SPOD**

Table 11 presents the number of trucks required at each transshipment node. In the Busan scenario, 307 trucks are required at eight transshipment nodes. Similarly in the

scenario of Kwangyang, 315 trucks are required at six transshipment nodes. Yjeongbu (node 7) is the busiest railway station when only Busan SPOD is operated. On the other hand, Yongin (node 4) is the busiest railway station in the Kwangyang SPOD scenario.

Busan SPOD		**Kwangyang SPOD**	
Transshipment node	**Trucks required**	**Transshipment node**	**Trucks required**
1	12	3	33
2	41	4	87
3	33	5	17
4	1	S	16
5	12	P	86
7	49	D	76
P	75		
D	84		
Total	307	Total	315

Table 11. **Trucks requirements using a single SPOD**

V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

In this thesis, we have studied a military long-haul transportation problem using a service network design and multi-modal transportation. We have applied our formulation to a transportation problem for ROK's military in a realistic scenario. The outcome of our MLTM is desirable for the military transportation planers to guide them on how to better establish the transportation services and allocate their resources.

We have demonstrated MLTM by comparing its solution with current practice for WTP planning, which is represented by a heuristic method. Our MLTM can reduce the transportation cost up to 29% from the current WTP planning. The main reasons for this result are: the activation of multi-modal transportation; service sharing by multiple demands, which is explicitly enabled in MLTM; and, the guarantee that the solution is optimal (given the modeling assumptions).

The total share of convoy use decreases by 65% (from 69% in the heuristic to 4% in the optimal MLTM solution), but the percentages for train and ship increase by 28% (from 31% to 59%) and 37% (from 0% to 37%), respectively. This is especially significant because a wartime scenario would have civilian evacuation from GSMA towards the south severely congesting the highways that convoys would use. Waterways are used at their maximum capability, as the most economical transportation means. To meet the demand in ARRS, six trips by convoy, 14 trips by train, and two trips by ship are required. Also, to complete delivery to the final destinations, 297 trucks are required.

We have compared two single-SPOD scenarios, Busan and Kwangyang, under the assumption that either SPOD has been temporarily shut down by enemy attacks. Both scenarios can meet the demand, but we find that losing Busan SPOD is more expensive than losing Kwangyang SPOD. In case of using Busan SPOD only, the total transportation cost is 3.7% higher than using both SPODs, but 5.0% lower than using Kwangyang SPOD only. In the Busan SPOD scenario, more train services and less convoy services are needed than in the Kwangyang SPOD scenario. This, which bears

most of the total cost difference, is explained because Busan SPOD has a well-developed railway infrastructure.

Finally, we outline some possible areas of future research:

- Further study of MLTM can exploit the multi-commodity nature of our problem. Our MLTM scenario handles a single type of commodity identified as a container with a certain capacity. However, the real military problem has multiple commodities (e.g., fuel, ammunition, and perishable items) which should be delivered separately by using different services, and even with pre-specified delivery times.
- Our scenarios consider a one-directional demand from two source nodes to thirteen sink nodes. Accordingly, services are assumed to be round-trip, but MLTM does not make any provisions to take advantage of this feature in order to serve possible demands in the opposite direction.
- While our MLTM finds the optimal routes and service frequencies to satisfy the demand, it is still necessary to complement it with a second stage. This would study a detail transportation schedule given MLTM outputs.
- Further analysis may extend MLTM to the civil industry problem.
- A more precise model should account for additional wartime load on the ROK transportation system placed by a civil evacuation from GSMA (47.1% of the population) southward on the highways.

APPENDIX: SOLUTION LISTINGS

1. SOLUTION USING TWO SPODS

Solving for ROKTRANS problem

Total cost is 463049

Unmet demand is 0

Services of type Convoy

Service SH_B_2 frequency of 1 require 1 Convoy

Service SH_K_1 frequency of 5 requires 2 Convoys

Services of type Truck

Service SH_2_2 frequency of 163 requires 41 Trucks

Service SH_3_3 frequency of 132 requires 33 Trucks

Service SH_4_4 frequency of 68 requires 17 Trucks

Service SH_5_11 frequency of 35 requires 12 Trucks

Service SH_7_9 frequency of 92 requires 24 Trucks

Service SH_7_10 frequency of 14 requires 5 Trucks

Service SH_P_4 frequency of 60 requires 19 Trucks

Service SH_P_8 frequency of 98 requires 35 Trucks

Service SH_P_10 frequency of 67 requires 27 Trucks

Service SH_D_5 frequency of 91 requires 39 Trucks

Service SH_D_11 frequency of 12 requires 7 Trucks

Service SH_D_12 frequency of 47 requires 17 Trucks

Service SH_D_13 frequency of 75 requires 21 Trucks

Services of type Train

Service SR1_B_S frequency of 7 requires 14 Trains

Service SR2_B_7 frequency of 3 requires 6 Trains

Service SR5_K_S frequency of 3 requires 6 Trains

Service SR6_K_7 frequency of 1 requires 2 Trains

Services of type Ship

Service SW_B_D frequency of 1 requires 4 Ships

Service SW_K_P frequency of 1 requires 4 Ships

Routes for demand W1

Route R79 handles 47 TEUs

Routes for demand W2

Route R2 handles 4 TEUs

Route R14 handles 154 TEUs

Route R33 handles 9 TEUs

Routes for demand W3

Route R92 handles 82 TEUs

Route R106 handles 50 TEUs

Routes for demand W4

Route R96 handles 68 TEUs

Route R139 handles 60 TEUs

Routes for demand W5

Route R75 handles 91 TEUs

Routes for demand W6

Route R25 handles 51 TEUs

Routes for demand W7

Route R26 handles 145 TEUs

Routes for demand W8

Route R143 handles 98 TEUs

Routes for demand W9

Route R46 handles 92 TEUs

Routes for demand W10

Route R47 handles 14 TEUs

Route R145 handles 67 TEUs

Routes for demand W11

Route R41 handles 35 TEUs

Route R76 handles 12 TEUs

Routes for demand W12

Route R77 handles 47 TEUs

Routes for demand W13

Route R78 handles 75 TEUs

2. SOLUTION USING BUSAN SPOD

Solving for B_ROKTRANS problem

Total cost is 480216

Unmet demand is 0

Services of type Convoy

Service SH_B_2 frequency of 1 requires 1 Convoys

Services of type Truck

Service SH_1_1 frequency of 47 requires 12 Trucks

Service SH_2_2 frequency of 163 requires 41 Trucks

Service SH_3_3 frequency of 132 requires 33 Trucks

Service SH_4_4 frequency of 1 requires 1 Trucks

Service SH_5_11 frequency of 35 requires 12 Trucks

Service SH_7_9 frequency of 92 requires 24 Trucks

Service SH_7_10 frequency of 81 requires 25 Trucks

Service SH_P_4 frequency of 127 requires 40 Trucks

Service SH_P_8 frequency of 98 requires 35 Trucks

Service SH_D_5 frequency of 91 requires 39 Trucks

Service SH_D_11 frequency of 12 requires 7 Trucks

Service SH_D_12 frequency of 47 requires 17 Trucks

Service SH_D_13 frequency of 75 requires 21 Trucks

Services of type Train

Service SR1_B_S frequency of 9 requires 18 Trains

Service SR2_B_7 frequency of 5 requires 10 Trains

Service SR3_B_S frequency of 1 requires 2 Trains

Services of type Ship

Service SW_B_P frequency of 1 requires 4 Ships

Service SW_B_D frequency of 1 requires 4 Ships

Routes for demand W1

Route R49 handles 47 TEUs

Routes for demand W2

Route R2 handles 4 TEUs

Route R14 handles 121 TEUs

Route R33 handles 42 TEUs

Routes for demand W3

Route R19 handles 132 TEUs

Routes for demand W4

Route R23 handles 1 TEUs

Route R68 handles 127 TEUs

Routes for demand W5

Route R75 handles 91 TEUs

Routes for demand W6

Route R25 handles 51 TEUs

Routes for demand W7

Route R26 handles 145 TEUs

Routes for demand W8

Route R72 handles 98 TEUs

Routes for demand W9

Route R46 handles 92 TEUs

Routes for demand W10

Route R47 handles 81 TEUs

Routes for demand W11

Route R41 handles 35 TEUs

Route R76 handles 12 TEUs

Routes for demand W12

Route R77 handles 47 TEUs

Routes for demand W13

Route R78 handles 75 TEUs

3. SOLUTION USING KWANGYANG SPOD

Solving for K_ROKTRANS problem

Total cost is 504052

Unmet demand is 0

Services of type Convoy

Service SH_K_1 frequency of 5 requires 2 Convoys

Service SH_K_2 frequency of 17 requires 8 Convoys

Services of type Truck

Service SH_3_3 frequency of 132 requires 33 Trucks

Service SH_4_4 frequency of 128 requires 32 Trucks

Service SH_4_6 frequency of 51 requires 14 Trucks

Service SH_4_7 frequency of 145 requires 41 Trucks

Service SH_5_5 frequency of 1 requires 1 Trucks

Service SH_5_11 frequency of 47 requires 16 Trucks

Service SH_S_9 frequency of 46 requires 16 Trucks

Service SH_P_8 frequency of 98 requires 35 Trucks

Service SH_P_9 frequency of 46 requires 18 Trucks

Service SH_P_10 frequency of 81 requires 33 Trucks

Service SH_D_5 frequency of 90 requires 38 Trucks

Service SH_D_12 frequency of 47 requires 17 Trucks

Service SH_D_13 frequency of 75 requires 21 Trucks

Services of type Train

Service SR5_K_S frequency of 8 requires 16 Trains

Service SR6_K_7 frequency of 3 requires 6 Trains

Services of type Ship

Service SW_K_P frequency of 1 requires 4 Ships

Service SW_K_D frequency of 1 requires 4 Ships

Routes for demand W1

Route R79 handles 47 TEUs

Routes for demand W2

Route R80 handles 167 TEUs

Routes for demand W3

Route R92 handles 30 TEUs

Route R106 handles 102 TEUs

Routes for demand W4

Route R96 handles 128 TEUs

Routes for demand W5

Route R110 handles 1 TEUs

Route R146 handles 90 TEUs

Routes for demand W6

Route R98 handles 51 TEUs

Routes for demand W7

Route R99 handles 145 TEUs

Routes for demand W8

Route R143 handles 98 TEUs

Routes for demand W9

Route R103 handles 46 TEUs

Route R144 handles 46 TEUs

Routes for demand W10

Route R145 handles 81 TEUs

Routes for demand W11

Route R113 handles 47 TEUs

Routes for demand W12

Route R148 handles 47 TEUs

Routes for demand W13

Route R149 handles 75 TEUs

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